An Overview of Lightning Research in Switzerland

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***Abstract*—In this paper, we address two questions asked by the organizers of the World Meeting on Lightning: 1) What has been, in your opinion, your most Important contribution to lightning research? and 2) in your opinion, what lightning research issues should be given special attention in the coming years?**

Keywords—lightning; lightning research; modeling; measurements; LEMP; electromagnetic coupling; tall towers; LEMP shielding; lightning location systems; climate change.

I. Introduction

In this paper, we address two questions posed by the initiators of the World Meeting on Lightning: The main contributions of our own research in the lightning field and the lightning research issues that should be given special attention in the coming years. The research performed by the authors in the past few decades has followed in the footsteps of pioneering work done in Switzerland by Berger and co-workers and through collaborative efforts with research groups from universities around the world. To take into account this context, we have organized this paper as follows: In Section II, we present from a historical point of view the work of Berger and his co-workers. Section III is devoted to the salient contributions in which the authors have been involved. In Section IV we present what we have selected, with an inevitable measure of subjectivity, as our main contribution: The setting up and main results of the instrumented Säntis tower in Switzerland. Finally, in Section V, entitled Priority Issues in Lightning Research, we attempt to answer the question of the lightning research issues that should be given special attention in the coming years.

II. Pioneering Work of Berger and Co-Workers (1940s-1970s)

The most widely referenced and most comprehensive dataset to date on lightning return stroke currents measured on short instrumented towers was presented by Berger and co-workers [1, 2]. The measurements were made on two 70-m tall towers including the steel needle that acts as a lightning rod, built on Mount San Salvatore in Lugano. Mount San Salvatore has a height of 640 m above the level of the adjacent Lake Lugano and it is 914 m above sea level. The first tower for lightning measurements was constructed on the summit of San Salvatore Mountain in 1943. It was replaced by a radio and television tower in 1958, on which the measurement of lightning discharges continued. In 1950, a second lightning research tower was constructed 400 m to the North from the first one. Both towers were 70 m tall. Later, the second tower was demolished and nowadays only the TV and radio tower is present on the summit of the mountain. Lightning currents were measured by means of a two-stage shunt just below the needle of each tower and recorded by cathode ray oscillographs. Berger also conducted high-speed photographic observations at Monte San Salvatore [3].

The work of Berger and his colleagues was truly pioneering and much of the modern knowledge on the lightning discharge is due to him. His important research contributions have resulted in a better understanding of the physics of the lightning discharge and its characteristics.

III. New Chapter: 1980s-Today

In the late 1980s, under the impulse of Professor Michel Ianoz and in cooperation with Prof. Carlo Mazzetti (University of Rome “La Sapienza”) and Prof. Carlo Alberto Nucci (University of Bologna), activities in lightning research were initiated at the Swiss Federal Institute of Technology (EPFL), Lausanne. At that time, the authors started working together while they were carrying their PhD studies (M. Rubinstein at the University of Florida and F. Rachidi at EPFL, respectively under the supervision of Profs. Martin Uman and Michel Ianoz). A summary of the salient research work carried out until today is presented in the next subsection and in Section IV.

A. Lightning Return Stroke Modeling

- Development of the MTLE return stroke model in collaboration with the Universities of Bologna and Rome [4, 5].
- Development of equations allowing to infer lightning currents from remote electromagnetic fields for various return stroke models [6].
- Development of a model for lightning return strokes taking into account the Doppler frequency shift

occurring as a result of reflection at the extending end of the return stroke. The derived expression is in agreement with the relativistic Doppler effect and is consistent with the Lorentz transformation [7, 8].

B. *Lightning Electromagnetic Field Computation*

- Development of analytical expressions for electromagnetic fields radiated by a lightning discharge [9-11]
- Derivation of an approximate formula for the calculation of horizontal electric field from lightning [12]. This formula has found extensive applications in lightning-related studies and is widely used in the literature (e.g., [13]).
- Full-wave computation of lightning electromagnetic fields and validity assessment of simplified approaches [14-16].
- Analysis of lightning electromagnetic field propagation along stratified soil or mixed propagation paths [17-20].
- Development of a model for the evaluation of the electric field associated with the lightning-triggering rocket wire and its corona [21].

C. *Lightning Electromagnetic Field Measurements*

- Simultaneous measurements at the NASA Kennedy Space Center of lightning return stroke current, and electric and magnetic fields at very close range (down to 30 m, the closest measurement to the lightning channel ever made by that time). The obtained experimental data obtained using artificially-initiated lightning resulted in a better understanding of the lightning phenomenon and in the characterization of the very close electromagnetic fields [22].
- Simultaneous measurements of return stroke current, the corresponding electric and magnetic fields at three distances associated with lightning strikes to the Toronto CN Tower were performed during the Summer of 2005 [23]. The data have been used to test engineering models extended to take into account the presence of an elevated strike object [24, 25].

D. *Lightning Interaction with Tall Towers*

- Derivation of a closed-form expression in the frequency domain to calculate the lightning current at any height along a strike object taking into account reflections at the top and at the bottom. An expression was also derived to calculate the reflection coefficient as a function of frequency at the bottom of the lightning strike object from two currents measured at different heights along the strike object [26].
- Expressions relating lightning return stroke currents and far radiated electric and magnetic fields, taking into account the presence of the elevated strike object, were derived and tested versus sets of simultaneously-measured currents and fields associated with lightning strikes to the CN Tower in Toronto, and reasonable agreement was found [27, 28]. These expressions may be used when lightning currents are measured directly on instrumented towers to calibrate the performance of lightning location systems.
- Based on a distributed-source representation of the lightning channel, the mathematical formulations of the so-called engineering lightning return stroke models were generalized to take into account the presence of a vertically-extended strike object [29].
- Analysis and evaluation of the number of upward flashes from tall structures [30, 31].

E. *Lightning-Induced Effects*

1) *Field-to-transmission line coupling models*

- Different models have been proposed in the literature to describe the interaction of lightning electromagnetic fields with transmission lines. A comprehensive study was performed in order to assess these models and it was shown, in particular, that in a model which is extensively used in the power literature a source term is incorrectly omitted, and that this omission may lead to important underestimation of lightning-induced voltages [32, 33].
- A model describing the coupling of an external electromagnetic field to a transmission line was developed which presents the advantage of being solely in terms of magnetic field components [34]. This model is now being used by several researchers in various fields of electromagnetic compatibility.

2) *LEMP Coupling to Overhead Lines*

- Various studies on LEMP coupling to overhead power lines (e.g., [35-39]).
- Lightning-induced on overhead lines taking into account the frequency-dependence of soil parameters [40].

3) *Coupling to Buried Cables*

- Modeling LEMP coupling with buried cables [41].
- Effect of dispersive and stratified ground on induced voltages on buried cables [42-44].

4) *Experimental Validation*

- Measurements of voltages induced from triggered lightning and model validation (overhead lines: [45-47], buried cables: [48, 49].

F. *Transient Analysis of Grounding Systems*

- A Comparison of Frequency-Dependent Soil Models: Application to the Analysis of Grounding Systems [50].

G. *LEMP Shielding*

- Numerical analysis of the electromagnetic shielding of buildings against LEMP [51, 52].

H. Lightning Location Systems

- Development of statistical methods for the estimation of the detection efficiency of adjacent lightning location systems [53, 54]).
- Statistical estimation of current parameters from remote field measurements [55].
- Development of a new method for locating lightning using electromagnetic time reversal [56, 57].
- Analysis of the effect of mountainous terrain on the performance of lightning location systems [58].

IV. Swiss Experimental Station for Lightning at Mount Säntis

Starting in 2008, a new research project was funded by the Swiss National Science Foundation which allowed the instrumentation of the Säntis tower in Switzerland for the measurement of lightning currents. This tower is struck by lightning more than 100 times a year and it represents a unique structure to collect experimental information related to lightning discharges. The Säntis station has been instrumented using advanced and modern equipment including remote monitoring and control capabilities for an accurate measurement of lightning current parameters ([59-61]). In the first five years of the operation of the station, more than 500 flashes were recorded. The obtained data constitutes the largest dataset available to this date for upward negative flashes. Some of the salient results obtained using the observations at the Säntis tower are as follows:

- Derivation of lightning current parameters for upward negative flashes [62].
- Characteristics of positive upward flashes [63].
- Evaluation of the performance o lightning location systems [64].

V. Priority Issues in Lightning Research

In spite of the very active and successful efforts of numerous research teams in the last 100 years or so, there is still much to be learnt about the physics of the lightning discharge and its effects. The continuation or initiation of basic and applied research for the years to come will likely be fueled by three main drivers:

1) *Scientific Curiosity*. Many aspects of the phenomenon are still poorly or not fully understood, including the initiation of natural and tower lightning, charge separation in the clouds, transient luminous events, modelling of various processes in different types of lightning discharges.

2) *The availability of new technological and methodological tools*. These include:

- Very high-speed video;
- Lightning mapping to "view" discharge processes within the clouds;
- Improved lightning detection and location, inexpensive, low power consumption sensor networks that could see large-scale deployment around the world;
- Drones (to make measurements where they have not been made before), and
- Developments in big data and artificial intelligence.

3) *The needs created by new trends in technology and human activity*. The use of renewable energy sources that are vulnerable to lightning, the use of smaller, sensitive, ubiquitous electronics in smart grids, transportation, internet of things, etc., the use of new materials, climate change, leading to changes in the lightning phenomenon itself.

Although the work listed under all three drivers is important, we select one point, which in our opinion, should be given priority.

Climate Change and Lightning

As a consequence of climate change, lightning's importance is set to increase as its level of incidence, its characteristics, and its intensity could be affected by modified weather patterns and as we move to more vulnerable renewable sources of energy, such as wind and solar farms. This will be exacerbated by the trend to use composite materials on wind turbines and aircraft and by the use of smaller, more sensitive electronics. Changes in lightning incidence and characteristics are also likely to influence the global electrical circuit (e.g., [65]).

Preliminary research indicates a possible correlation between the number of lightning flashes and the temperature [66, 67]. A correlation has also been observed between climate change and deforestation [68]. Current lightning protection standards, largely based, as mentioned in Section II, on the work of Berger and co-workers, do not account for the possible increased risk due to climate change. Indeed, Berger's measurements were made last century and most climate change models predict an increase in the severity of weather phenomena. The degree of complexity and the accuracy of these models at the local level are insufficient to use them with confidence for decision making regarding early development and application of preventive measures against increased lightning risks at the regional scale.

Large amounts of historical lightning data available are being gathered by earth-based and satellite lightning detection, observation and location systems worldwide. In addition, direct lightning current measurements are gathered every year on instrumented towers in Switzerland, Germany, Austria, Brazil, Canada, Japan, Russia and China. Moreover, deforestation data are being collected from satellite imagery at increasing resolution (currently 30 m) and, if the trend continues, it will improve to a few meters within years. These data could be exploited with the help of expert knowledge for the extraction of patterns and the development of models at the global and regional levels that could serve as decision-making aids and warning systems, both short term and long term, regarding the lightning risk linked to climate change. In addition, the potential also exists to use the lightning data as an indicator of climate change level and climate change pace.

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